

# Intensity-Modulated Continuous-Wave Lidar at 1.57 $\mu\text{m}$ for Atmospheric CO<sub>2</sub> Measurements

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## 1. Overview of Intensity Modulated Continuous Wave Lidar Approach

The NASA Langley Research Center (LaRC) and ITT Exelis, Inc. (Exelis) have been jointly developing and testing advanced lidar technologies for the Active Sensing of CO<sub>2</sub> Emissions over Nights, Days and Seasons (ASCENDS) space mission. A critical aspect of these activities is the development of a prototype Intensity-Modulated Continuous-Wave (IM-CW) lidar for high-precision, column CO<sub>2</sub> mixing ratio (XCO<sub>2</sub>) measurements using the Integrated Path Differential Absorption (IPDA) approach. Airborne flight campaigns have demonstrated that the CO<sub>2</sub> measurements of current IM-CW lidar system meet the accuracy and precision requirements of the ASCENDS mission. Furthermore, analyses of space CO<sub>2</sub> measurements show that this lidar technology and approach will enable the ASCENDS mission to achieve its science goals.

The first IM-CW lidar system, called the Multifunctional Fiber Laser Lidar (MFLL) developed by Exelis (Dobbs et al. 2008; Dobler et al. 2013), was used to demonstrate the capability of CO<sub>2</sub> column measurements from several aircraft under a variety of atmospheric and surface conditions (Browell et al., 2008, 2009, 2010, 2012; Dobler et al., 2013). Extensive demonstrations have been conducted in laboratory and horizontal ground test-range environments and in flight campaigns. The MFLL CO<sub>2</sub> column measurements over desert and vegetated surfaces have been found to agree with those calculated from in-situ measurements of atmospheric meteorological and CO<sub>2</sub> profiles to within an average of 0.17% or ~0.65 ppmv. A measurement precision of 0.08% or ~0.3 ppmv for a 10-s average over these surfaces has also been achieved (Browell et al., 2009; Dobler et al., 2013).

## 2. Basic characteristics of IM-CW lidar system

The lidar discussed here is based on the airborne prototype system MFLL (Dobbs et al., 2007, 2008; Dobler et al., 2013; Lin et al., 2013). Figure 1 shows the concept of the lidar design (left) and the MFLL lidar onboard the NASA DC-8 aircraft (right). The main parameters of the instrument are listed in Table 1.

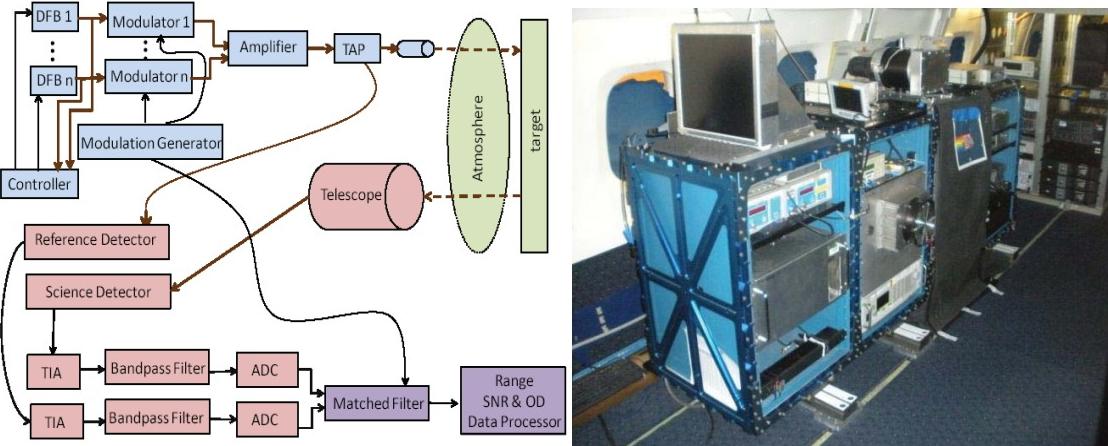


Figure 1 (left) Architecture of the airborne prototype lidar; (right) The MFLL lidar mounted inside the NASA DC-8 aircraft. The onboard data processing and onboard display unit, detection system, and CO<sub>2</sub> transmitter subsystems are seen from front to back. The telescope and transmit optics are housed under the black laser curtain.

The lidar system has one laser wavelength positioned at the center of the CO<sub>2</sub> absorption line at 1571.112 nm (called the “online”) and two other laser wavelengths in the distant wings of the absorption line at offsets of ±50 pm (called the “offlines”) for the CO<sub>2</sub> IPDA measurements. The wavelengths were selected to minimize water vapor and other trace gas interferences on the IPDA measurements and to simultaneously maximize the signal-to-noise ratio (SNR) of the differential absorption optical depth (DAOD) measurements (Ismail et al., 1989; Remsberg and Gordley, 1978). The altitude-dependent gas absorption weighting function; the DAOD sensitivity to knowledge of the laser wavelength and line-width; and the wavelength stability of the laser spectra are other major considerations in the laser line selections (Menzies and Tratt 2003; Ehret et al., 2008; Kameyama et al., 2010; Lin et al., 2013). For range determination, a range-encoded IM technique, swept frequency, has been applied to the lidar system. This results in the advanced range measurement and cloud/aerosol discrimination, which is an essential capability to achieve precise XCO<sub>2</sub> measurements. After receiving lidar returns, the key element for the processing of detected lidar signals is the matched filter that correlates the transmitted IM laser waveforms with the received lidar signals reflected from the

**Table 1 Airborne MFLL Lidar Parameters**

Seed laser type:	DFB diode laser
Line width	< 6 MHz each wavelength
Side mode suppression	Ratio > 45 dB
CO <sub>2</sub> lines: (vacuum)	1.571112 μm (On), 1.571061 μm (Off 1), 1.571161 μm (Off 2)
Modulator:	Semiconductor Optical Amplifier
Modulation type:	Intensity-modulated continuous-wave (IM-CW)
Optical amplifier:	CO <sub>2</sub> : EDFA
Output power:	5 Watts for CO <sub>2</sub>
Optical bandpass filter:	2.4 nm
Telescope	Cassegrain, 8 in. diameter.
Optical throughput	8.5%
Detector	DRS; HgCdTe APD gain: ~940; Excess noise factor ~1.3; 77 K as operated
Transimpedance amplifier	Gain: 10 <sup>6</sup>
Sample rate	2 MHz
Swept-frequency:	~350 ± 250 KHz;
Unambiguous range:	15-km; 30-km (after 2012)
Laser divergence angle:	190 urad (half angle)
Receiver FOV:	240 urad (half angle)
Receiver duty cycle:	100%
Reporting interval:	0.1 sec (10 Hz)

the capability in making remote CO<sub>2</sub> and XCO<sub>2</sub> column measurements for the ASCENDS mission (Dobler et al., 2013). Accurate CO<sub>2</sub> column measurements have been demonstrated by these comprehensive aircraft flight tests. For example, 1-second averaged CO<sub>2</sub> column measurements over desert regions resulted in high precision measurements with SNR of DAOD (SNR<sub>DAOD</sub>) higher than 600 (Browell et al., 2012; Dobler et al., 2013). Figure 2 shows two comparison examples of 1-s MFLL CO<sub>2</sub> DAOD measurements and in-situ-derived (modeled) values in drastically different geographic regions.

The top panel of Figure 2 shows the CO<sub>2</sub> measurements on a constant altitude flight leg over the Central Valley, CA in comparison to modeled DAOD values derived from in-situ CO<sub>2</sub> data of a DC-8 spiral at the center of the leg and radiosonde data obtained within about 1 hour of the over-flight. The small variations in the in-situ-derived (i.e., modeled) DAOD across the flight leg were due to small changes in the range from the aircraft to the surface. The resulting difference of 1-s averages between the measured and modeled DAOD values on the Central Valley flight leg was found to be -0.28% or the equivalent of ~1.1 ppmv. The bottom panel shows the DAOD comparison while transiting across the Rocky Mountains. The in-situ data (spiral and radiosonde) came from

surface as well as clouds. From matched filter outputs, the location and magnitude of correlation peak powers are obtained and used to estimate the range and DAOD, respectively. The accuracy of range estimates was found to be better than 3 m from ground-range and flight campaigns (Dobler et al., 2013; Lin et al., 2013). Details on the instrument and data processing can be found in Dobler et al. (2013) and Lin et al. (2013).

### 3. Airborne demonstration of CO<sub>2</sub> measurements

To evaluate the accuracy and precision of the MFLL remotely-sensed CO<sub>2</sub> column measurements, actual CO<sub>2</sub> DAOD values are needed. These values were derived based on the knowledge of the in-situ observed vertical profiles of XCO<sub>2</sub> and meteorological conditions; the meteorologically-dependent spectroscopy of CO<sub>2</sub> and any interfering gas, such as water vapor; the path length from the aircraft to the surface; and the off-nadir pointing of the laser beam (Browell et al., 2008, 2010, 2012; Dobler et al., 2013; Lin et al., 2013). High-quality in-situ measurements of XCO<sub>2</sub> (Choi et al., 2008; Vay et al., 2003), temperature (T), pressure (P), and relative humidity (q) profiles and other meteorological conditions were obtained from onboard instruments during aircraft spirals and collocated with contemporaneous radiosonde launches. A laser altimeter was also included to make an independent measurement of the range to the surface and cloud tops. A GPS and the aircraft navigation system provided additional aircraft altitude and attitude information. Comparisons of MFLL remotely sensed and in-situ-derived DAOD values were typically limited to a horizontal distance of less than 10 km of the aircraft spiral and radiosonde locations. When multiple in-situ spirals were conducted during a flight, the spiral data corresponding to the closest MFLL overpass time were used.

The LaRC ASCENDS team has conducted a total of 13 flight campaigns with various aircraft such as NASA UC-12 and DC-8 since May 2005 to evaluate

Railroad Valley, NV, and the variation in DAOD values across the mountains was almost entirely due to surface elevation changes as the aircraft was at a constant altitude. The comparison of 1-s measured and modeled DAOD values demonstrated a high level of agreement ( $\Delta\text{DAOD} = -0.44\%$  or  $\sim 1.7 \text{ ppmv}$ ) even when one expects some change in  $\text{CO}_2$  across the mountains that could not be captured in the modeled DAOD due to the lack of in-situ data. Flight tests of the current lidar instrument have demonstrated very high-precision  $\text{CO}_2$  DAOD measurements of  $\text{SNR}_{\text{DAOD}} > 1300$  with a 10-s averaging interval (Browell et al., 2012; Dobler et al., 2013).

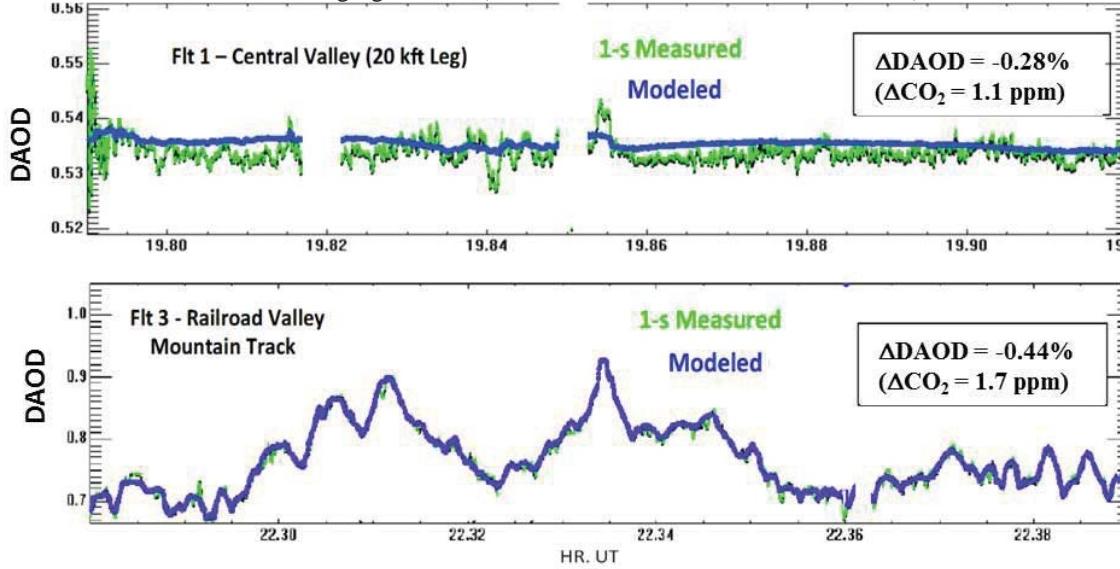


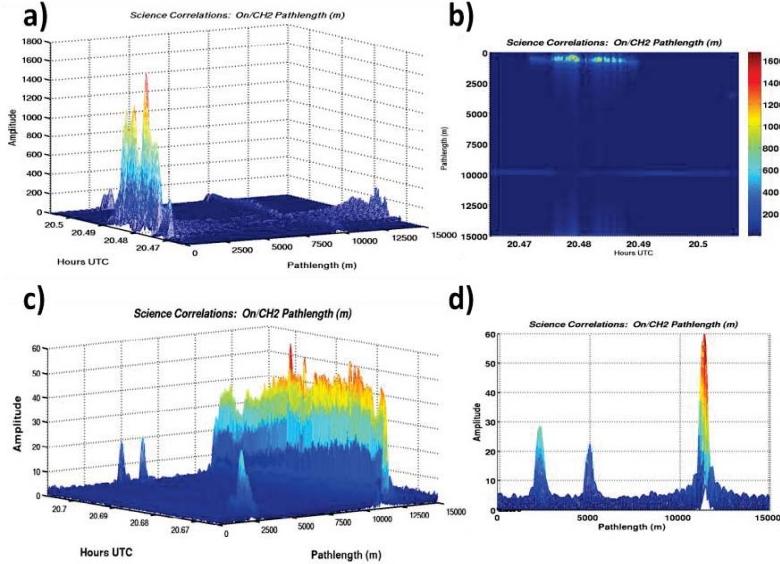
Figure 2 Comparison of airborne measured and modeled  $\text{CO}_2$  DAODs for flights over California's Central Valley (top) and the Rocky Mountains (bottom) in route to Railroad Valley, NV.

Since variations in surface types and reflectance can significantly affect lidar return powers and  $\text{CO}_2$  column retrievals, different surface conditions were analyzed from MFLL flight data. For farm fields and deserts, moderate to high reflectance values were observed, and strong signals for  $\text{CO}_2$  column retrievals were received. For some surfaces especially snow, ice, and rough water surfaces, very low reflectance was expected and observed. From MFLL data, the measured surface reflectance of snow and ice was as low as about 0.02/sr. Fresh snow (less than 1-2 days old) was found to have even significantly lower reflectance (about  $\sim 0.01/\text{sr}$ ). Even in these low reflectance cases, enough backscattered signal was obtained for  $\text{CO}_2$  column retrievals from high altitude flight legs (Nehrir et al. 2013). The variability in the surface reflectance for complete snow covered terrain was found to be relatively homogeneous, however the magnitude of the surface reflectivity for both snow covered mountainous and farmland terrain was observed to vary by more than an order of magnitude over distances of less than 10-20 meters from the nominal snow and ice surface reflectance values (Nehrir et al. 2013).

In addition to surface types, the presence of thin clouds and aerosol layers are an important factor that affects the accuracy of  $\text{CO}_2$  column measurements. The capability for discrimination of cloud/aerosol returns from ground returns is achieved using the swept frequency IM approach as shown in Figure 3. The data were obtained from the DC-8 flight on 4 August 2011 over Railroad Valley, NV (Harrison et al. 2013). Distinct ranges and reflections of the surface and clouds were observed from the swept-frequency IM measurements. The presence of intermediate thin clouds can decrease lidar return signals and reduce the precision of  $\text{CO}_2$  column estimates, but the  $\text{CO}_2$  measurements can still satisfy mission requirements when cloud attenuation scaling is considered (Lin et al. 2013). Ranging precisions of  $\sim 3 \text{ m}$  for these surfaces and clouds have also been achieved (Dobler et al. 2013; Harrison et al. 2013).

#### 4. Near-future development and advancing airborne IM-CW instruments to space

The key areas for LaRC near-term measurement development and demonstration include maturing low-mass high-power lasers, low noise detector subsystems, and real-time data processing electronics required for the ASCENDS space mission (Obland et al. 2012, 2013; Beyon et al. 2013) via the next generation airborne lidar system. LaRC team conducted ground tests at LaRC lidar test range in April 2014 and flight tests in July 2014 for this lidar system. Initial ground and flight data analysis indicates that the instrument has performed as expected and precise atmospheric  $\text{CO}_2$  measurements have been obtained. Another area for the demonstration is the cloud slicing technique, which is enabled by the ranging capability for lidar to measure  $\text{CO}_2$  DAOD values above clouds and to



**Figure 3** Range discrimination of cloud returns from ground returns using the swept frequency IM-CW approach. Panels a) and b) show 3-D and 2-D, respectively, representation of a large cloud return above a small ground return; panel c) shows the distribution of signals from weak clouds and strong ground return signals, and panel d) is a superposition of data from c) on a signal vs. path length.

presented statistically from simulation ensembles that include noise sources and the CO<sub>2</sub> measurement environments. The characteristics of simulated lidar system are based on existing technologies and their implementation in existing systems. Validations of the model show excellent agreement of simulated results with measurements.

For the ASCENDS space mission, the LaRC team has formulated a conceptual design of the space lidar based on current technologies. The architecture of this space lidar is similar to the prototype airborne lidar (c.f. Figure 1). Compared to the airborne lidar, the main changes for the space lidar sensor are using two sideline wavelengths with one at +3 pm (called Side-1) and the other at +10 pm (called Side-2) offset from the CO<sub>2</sub> absorption line center; increasing the transmitted laser output power to 42 W and the telescope diameter to 1.5 m; and reducing the optical bandpass filter bandwidth to 0.5 nm FWHM and laser half-angle divergence to 50  $\mu$ rad (Lin et al., 2013). The receiver's field of view is set to be 33% larger than that of laser divergence, and the optical throughput is 0.65. The sideline wavelengths are selected to avoid excessive absorption of the entire atmospheric CO<sub>2</sub> column at the line center and to have more weighting of the measurement across the mid to lower troposphere, where most of the CO<sub>2</sub> flux exchanges with ecosystems and advection within the atmosphere take place.

To understand the IM-CW lidar performance for space applications, model simulations are conducted for a sun-synchronous, dawn/dusk orbit (Ehret et al., 2008) with an altitude of 390 km. Under clear conditions, simulation shows that the precision of the DAOD measurements for surfaces similar to the playa of Railroad Valley, NV (reflectance 0.176 sr<sup>-1</sup>) will be better than 0.07% for 10-s averages. Clear-sky bias errors are found to be very small and below 0.04 % from the simulations. Including thin clouds with optical depths up to 1, the CO<sub>2</sub> SNR<sub>DAOD</sub> measurements with 0.1-s integration period for surfaces similar to that of Railroad Valley, NV will be greater than 94 and 65 for Side-1 and Side-2, respectively (Fig. 4a). The CO<sub>2</sub> column bias errors introduced by the thin clouds are  $\leq$ 0.1% for cloud optical depth  $\leq$ 0.4, but they could reach ~0.5% for more optically thick clouds with cloud optical depths up to 1 (Fig. 4b).

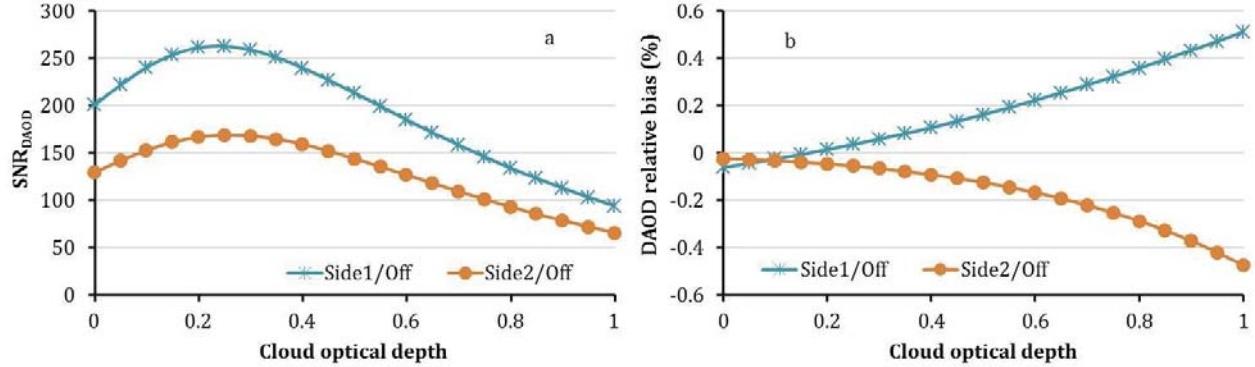
When the cloud and surface ranges and scattering amplitudes are obtained from the analysis of matched filter outputs, the cloud bias errors can be further reduced as seen from the compensating feature of the bias errors between the retrievals of the two sidelines (Fig. 4b). Other simulation studies indicate that the present space IM-CW lidar concept can provide ASCENDS required CO<sub>2</sub> measurements from not only the dawn/dusk orbit but also other Low

surfaces. The technique will provide the estimates of CO<sub>2</sub> columns across both the free troposphere and the planetary boundary layer.

Furthermore, advanced lidar intensity modulation algorithms that eliminate cloud bias errors on lidar surface returns when clouds are very close to the surface are developed (Campbell et al., 2013) and will be tested. Along with these efforts, modeling of lidar atmospheric CO<sub>2</sub> column measurements is also a key part of the measurement development and demonstration. The LaRC ASCENDS team has developed a model for lidar system and CO<sub>2</sub> measurement simulations (Lin et al., 2013). This model for lidar and its measurement environment is important to guide improvement of lidar systems and allows predictions of CO<sub>2</sub> measurements for future space missions. The model accounts for all fundamental physics and characteristics of the instruments and their related measurement environments. The model results are

presented statistically from simulation ensembles that include noise sources and uncertainties related to the lidar

Earth Orbits such as sun-synchronous, day/night orbits, maximizing the flexibility of the space instrumentation to various CO<sub>2</sub> measurement needs.



**Figure 4** Simulated 0.1-s results for a spaceborne lidar under thin cirrus cloud conditions. The CO<sub>2</sub> SNR<sub>DAOD</sub> (a) and relative bias error (b) values are calculated for the surface assuming the reflectance of Railroad Valley, NV.

## 5. Summary

The approach of an Intensity-Modulated Continuous-Wave 1.57  $\mu\text{m}$  lidar for atmospheric CO<sub>2</sub> measurements that NASA Langley Research Center and ITT Exelis, Inc. have been assessing has a great potential for applications to the ASCENDS space mission using the Integrated Path Differential Absorption technique. This approach takes the advantage of telecommunication technologies and can achieve required transmitted power and other key specifications of space instrumentation. Airborne flight campaigns of the current prototype IM-CW lidar systems have demonstrated high accuracy and precision CO<sub>2</sub> measurements in various atmospheric and surface conditions. Model simulations of atmospheric CO<sub>2</sub> measurements using this kind of lidar instruments under relevant space, atmospheric and surface environmental conditions have shown that this IM-CW lidar technology and approach will enable the ASCENDS space mission to meet its science goals.

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